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Analysis of Cutting Forces and Temperature in Laser Assisted Machining of Inconel 718 using Taguchi Method

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Abstract

This paper presents an experimental investigation of Laser Assisted Machining (LAM) of Inconel 718 using turning process. The experiments were planned according to Taguchi L9 orthogonal array of experimental design. The effects of laser cutting parameters, namely cutting speed, feed rate and laser power are considered as control factors to determine the effects on cutting forces and cutting temperature. The cutting tool used for machining is a multi-layered (TiCN/Al_2O_3/TiN)coated carbide insert. The optimal cutting conditions were determined using the Taguchi's Signal-to-Noise (S/N) ratio. The analysis of results reveals that cutting speed and laser power has maximum influence on the cutting force components compared to feed rate. It was also observed that there is no change in the hardness value (48 HRc) of the machined surface due to laser heating. Finally, the cutting forces were compared between conventional and laser assisted machining;a maximum of 60% reduction of cutting force was observed for LAM at optimal combinations.

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Keywords:Laser Assisted machining, Inconel 718,Nd:YAG laser, Laser power,cutting forces, cutting temperature, Taguchi Method

1. Introduction

Nickel based alloys especially Inconel 718 is one of the widely used material in aerospace industries with service temperature 650° C. The characteristics such as poor thermal properties, high-temperature strength, a tendency to severe work hardening and high tool workpiece affinity make the machining of Inconel 718 very difficult and considered as difficult-to-machine material [1]. Considerable research on conventional machining of Inconel 718 for analyzing cutting force, tool wear, surface roughness and chip morphology have been reported [2-5]. Machining of Inconel 718 with uncoated cemented carbide tool is limited to a low cutting speed of 60 m/min due to high

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mechanical and thermal loads which adversely affect the tool life [3-6]. To improve the process efficiency, new tool materials such as coated carbide tools (either PVD or CVD), coated CBN, PCBN and whisker reinforced ceramics cutting tool are frequently used as cutting tools for machining of Inconel 718 [7-9]. The TiAlN PVD coatings are used for machining of Inconel 718 when compared with TiN and TiCN coatings in terms of tool life [10]. Preheating the work materialis an attractive alternative technique for machining of hard-to-machine materials using cheaper ceramic and coated tools.The preheating reduces the hardness, strain hardening and yield strength of the material.

In recent years, the concept thermal enhanced machining was applied to various hard-to-machine materials [11-16].Various external heat sources such as gas torch, induction heating, furnace preheating, plasma and laser were employed for preheating the work material. For effective thermal enhanced machining the heating should be localized in front of the cutting tool and only the volume of material to be removed. The Localized heating softens only the chip or workpiece uncut material, leaving the workpiece relatively cool and metallurgically undamaged. [11]. Several researchers have used the laser energy to preheat the hard-to-cut material during machining and observed that there is a reduction in cutting force/specific cutting energy, improvement in surface finish of work material and tool life[17-20].

The two main laser sources which are widely used in LAM are CO_2 and Nd:YAG lasers. The latter having an advantage of shorter wavelength (1.06 μm) which results in better absorption of laser energy in metals (Inconel, hardened steel, Titanium), metal matrix composites and ceramics without any coating [21]. Most of the research works have been focused on the benefits of LAM and addressed the challenges in conventional machining. The machining results of LAM depend on both machining process parameters and laser parameters. The main operating parameters associated with laser assisted machining are: Laser power, spot diameter of the laser beam, cutting speed, feed rate and depth of cut. The optimal setting for LAM is difficult due to the many control parameters and their interactions. A statistical study based on design of experiments is needed to investigate the effect of process parameter and their interactions. The present work aims to analyze the machinability characteristics with special reference to cutting forces and surface temperature of Inconel 718 at different cutting conditions using Taguchi method. The influence of cutting parameters namely cutting speed (s), feed rate (f) and laser power (p) on the workpiece surface temperature (Ts) and the cutting forces (Fx, Fy, and Fz) were analyzed using main effect plots. The Taguchi Methodology has been used in this study to arrive the optimal setting of laser machining parameters. In addition to this, the present work highlights the general benefits of LAM compared with conventional machining.

2. Experimental Methods

2.1. Experimental setup

The experimental setup used for the present investigation is shown in Figure 1. The dry turning experiment were performed on a high speed lathe having maximum spindle speed of 3600 rpm and a drive motor power of 1.5 kW. An Nd:YAG solid state continuous wave laser(Supplied by JK laser©) with a maximum power of 2 kW and wavelength of 1.06 μm was used as a source for preheating the workpiece during experiments. The laser beam was focused at 60˚to the tool on the work piece surface with a focal length of 160 mm. The laser beam was delivered by a fiber optic cable of length 15 m long through a lens with a laser spot size of 2 mm. The laser head is mounted to lathe machine with a specially designed fixture for varying the position of laser beam and its spot size. Compressed air was used to protect the laser head lens from excess heat and damage due flow of chips. The location of surface temperature measurement is shown in Fig. 1 (b). The workpiece was rotated counter clockwise during laser heating tests. An infrared pyrometer was used to track the surface temperature of the workpiece. Each machining trail has been carried out for a cutting length of 60 mm with a new cutting edge. Cutting force was measured using 9257B type Kistler dynamometer. Prior to the experimental trials, a skin cut of 0.5mm thickness is done in order to remove any deformities on the surface.

2.2. Workpiece material

Inconel 718 with hardness of 48HRCand diameter of 25 mm is used as work material. Table 1 shows the chemical properties of Inconel 718 alloy. It is a precipitation hardenable nickel chromium alloy containing significant amount of iron, niobium and molybdenum along with lesser amounts of aluminum and titanium. The presence of chromium yields a high temperature oxidation resistance and other elements helps to guarantee for high temperature strength and creep resistance property [3].

Table 1. Chemical composition (wt %) of Inconel 718 alloy

Elements	C	Mn	Si	Ti	Al	Co	Mb	Cb	Fe	Cr	Ni
Percentage	0.08	0.35	0.35	0.6	0.8	1.0	3.0	5.0	17.0	19.0	52.82

2.3. Cutting tool material

The cutting tool selected for machining of Inconel 718 was CVD (TICN/Al2O3/TIN) coated carbide tungsten inserts (grade 6630). The ISO coding for the insert is CNMG 120408-EM.The grade 6630, MTCVD coated with a supporting thick layer TiCN and Al_2O_3 coating gives excellent wear and heat resistant properties. The measured hot hardness of TiCN is 4400 to 4600 HV. Table 2 shows the tool nomenclatures of cutting insert used in the present study.

Table 2.Cutting inserts used in LAM experiment

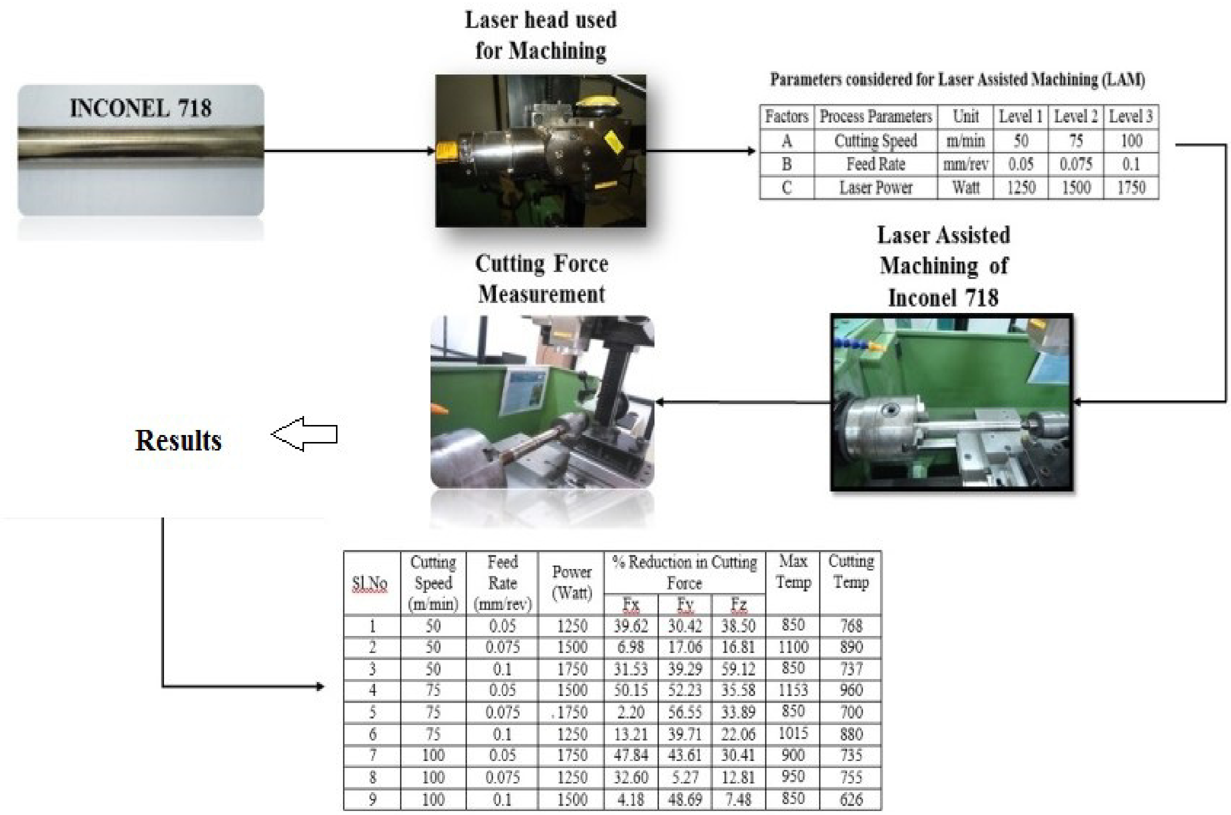
Rake angle (γ)	Clearance angle (α)	Inclination angle (η)	Approach angle (φ)	Included angle (β)	Nose radius r (mm)
-7˚	0˚	-6˚	75˚	90˚	0.8

2.4. Taguchi method-Design of experiments

Designs of experiments (DOE) are considered as a useful method for determining optimal cutting parameters from the experimental observations [28]. In this experimental study, orthogonal array (OA) has been used to find the effect of three process parameters (cutting speed, feed and laser power) on cutting force parameters and cutting temperature of laser assisted machining of Inconel 718. The cutting parameters selected for laser assisted turning operations are cutting speed (s), feed rate (f) and laser power (p). From the literature, it is observed that the influence of cutting speed/laser scanning speed and feed rate are more significant when compared to cutting depth. The experiments are planned using the Taguchi's orthogonal array. The machining tests were conducted according to a 3-level and 3-factor L9 orthogonal array. The cutting parameters and their levels are shown in Table 3. The experimental layout for the L9 orthogonal array is shown in Table 4. To obtain optimal cutting performance, the-lower-the-better quality characteristic for cutting force and lager the better characteristic for cutting temperature (Ts)were taken as shown in Eq (1) and Eq (2). The process flow chart of the experimental steps and optimization procedure are shown in Fig. 1

Table 3 Process parameters used at various levels

Process parameter	Unit	Level 1	Level 2	Level 3
Cutting Speed (s)	m/min	50	75	100
Feed rate (f)	mm/rev	0.05	0.075	0.1
Laser power (P)	W	1250	1500	1750



Factors	Process Parameters	Unit	Level 1	Level 2	Level 3
A	Cutting Speed	m/min	50	75	100
B	Feed Rate	mm/rev	0.05	0.075	0.1
C	Laser Power	Watt	1250	1500	1750

Sl.No	Cutting Speed (m/min)	Feed Rate (mm/rev)	Power (Watt)	% Reduction in Cutting Force			Max Temp	Cutting Temp
				Fx	Fy	Fz		
1	50	0.05	1250	39.62	30.42	38.50	850	768
2	50	0.075	1500	6.98	17.06	16.81	1100	890
3	50	0.1	1750	31.53	39.29	59.12	850	737
4	75	0.05	1500	50.15	52.23	35.58	1153	960
5	75	0.075	.1750	2.20	56.55	33.89	850	700
6	75	0.1	1250	13.21	39.71	22.06	1015	880
7	100	0.05	1750	47.84	43.61	30.41	900	735
8	100	0.075	1250	32.60	5.27	12.81	950	755
9	100	0.1	1500	4.18	48.69	7.48	850	626

Fig.1 Process flowchart for Experimental

The S/N ratio for cutting force (Fz) is calculated by taking into the consideration smaller-the-better characteristics by Eq. 1 (in decibel) and for Surface temperature (Ts) by Eq. 2 (in decibel) is given by

$$\frac{S}{N} = -10Log\left(\frac{1}{n}\sum_{i=n}^{n} y_i^2\right) \text{ ----------- (1)} \qquad \frac{S}{N} = -10Log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right) \text{---------- (2)}$$

Where 'n' is the number of measurements in a row, n=3 and
'y_i' is the i^{th} measured value in a row.

The mean S/N ratio of each parameter level has been calculated by averaging their corresponding levels in orthogonal array. The optimal parameters were chosen based on higher S/N ratio as the signal represents the desirable value and noise represents the undesirable value. Next, statistical analysis of variance (ANOVA) was conducted to study the significance of process parameters on responses based on their P-value and F-value at 95% confidence level. Finally, the optimal parameters are verified by conducting confirmation runs.

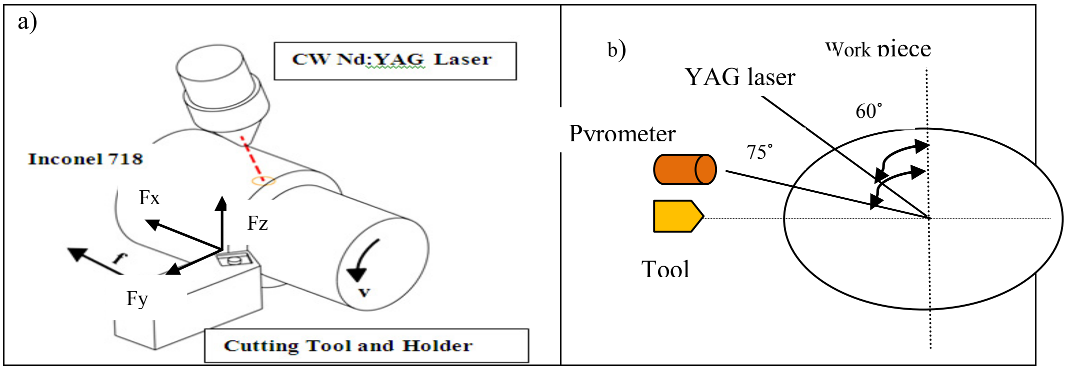


Fig.2. LAT experimental setup with Nd:YAG CW laser:(a)Schematic diagram, (b) Original setup.

2.5. Procedure

Inconel 718 alloy of diameter 25 mm and 300mm length washeld in the precision lathe using a three-jaw chuck. The workpiece was rotated in counter clock wise direction. The laser war irradiated at the workpiece surface for preheating the material. Once the required temperature is reached the feed was given to the tool. The turning experiments were carried out in dry cutting environment for a length of 60 mm. The experiments were repeated two times and average values were used for the analysis. The experimental set-up is shown in Fig. 2. The cutting force data and surface temperature were recorded during machining. The results obtained are presented in Table 4.

3. Results and Discussion

The experiments were performed according Taguchi's L9 orthogonal array and the results are tabulated in the Table 4. The cutting forces and surface temperature were measured for all the experiments. Fig.3 shows the typical force data and temperature data recorded during Expt. Sl. No. 6. This section presents the statistical analysis of cutting forces and surface temperature of work material during LAM. Also, the cutting force results of LAM and conventional machining are compared and discussed.

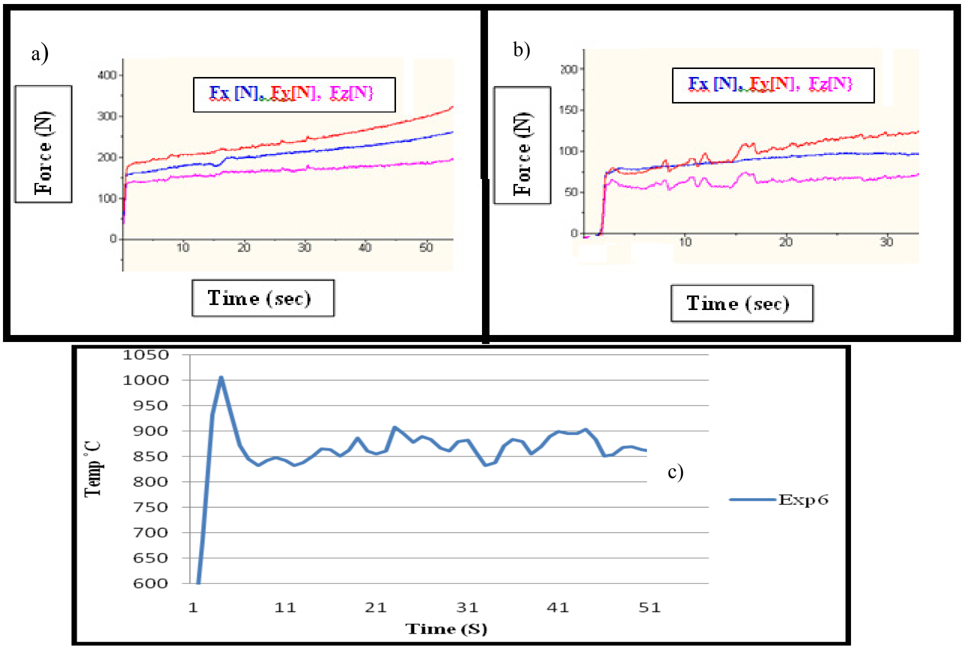


Fig.3 Force fluctuations for trial 6 a) Conventional machining b) Laser Assisted Machining c)Temperature profile

3.1Analysis of S/N ratio and ANOVA for cutting force and surface temperature

The effects of the laser cutting parameters on the responses were analyzed using the MINITAB® statistical software. The main effect and interaction effect are referred as two statistical analyses. In this, main effect is the effect which separate out the effect of each and every cutting parameter at different levels. The interaction effects are used to predict the effect of relationships between independent and dependent parameters on the object functions. According to Eq (1),S/N ratios of each measured values listed in Table 4 are calculated. Then, the mean S/N ratios at each level of process parameters are obtained by computing the average at corresponding levels. The main effect plots of S/N ratio results for the feed force (Fx), Thrust force (Fy) and cutting force (Fz) are shown in Fig. 4. It is evident from Fig 3 that with application of low laser powers in LAM will deliver more benefits during machining that cannot be recognized at highest laser powers. High laser powers will result in higher cutting force reductions as well as high cutting temperatures. So, LAM can be successfully implemented in the industrial environment with low laser power. However, at the laser spot the temperature produced should be within the limit otherwise deleterious effects of excessive surface heating will be observed. This attributed to surface damage and subsurface microstructure.

Results of analysis of means indicate that cutting speed and laser power is the most significant machining parameter followed by feed rate which affect the cutting force performance characteristics. From the main effect plot (Fig 4.), it is observed that the thrust force component have higher magnitude compared to other two component force. In the research work dealt by Bhatt [29] on finishing machining operations conventional machining of Inconel 718 using triple layered CVD ($TiCN/Al_2O_3/TiN$) coated WC tools having round insert geometry. It was observed that for low cutting speeds of 50 m/min the forces generated were higher. However, feed forces generated by this cutting inserts exhibited a drop as the feed increased. At medium cutting speed of 75 m/min and 0.1 mm/rev, these

Table 4 Experimental results

Sl.No	v m/min	f mm/rev	P W		LAM			
				FxkN	FykN	FzkN	Cutting Temp	Hardness HRC
1	50	0.05	1250	115.5	153.9	119.8	768	46
2	50	0.075	1500	187.8	234.4	203.9	890	48
3	50	0.1	1750	163.1	202.4	116.7	737	47
4	75	0.05	1500	129.1	152.4	124	960	45
5	75	0.075	1750	133.2	108.7	119.4	700	47
6	75	0.1	1250	116	58.9	77.62	880	47
7	100	0.05	1750	161.7	221.6	137.1	735	47
8	100	0.075	1250	182.6	208.6	137.5	755	47
9	100	0.1	1500	187.9	271.9	211.5	626	48

Table 5 Optimum values for Responses

Sl.No	Responses	Optimum Values
1	Feed Force (Fx)	75 m/min,1250 W, 0.05 mm/rev
2	Thrust Force (Fy)	75 /min,1250W,0.1 mm/rev
3	Cutting Force (Fz)	75 /m/min, 1250W, 0.1 mm/rev
4	Surface Temperature (Ts)	75 m/min, 1500W, 0.05 mm/rev

inserts had the lowest cutting, feed and thrust forces. At high cutting speeds this cutting inserts generated the highest forces in all three directions. Similarly trend was observed in LAM, the forces drops at 75 m/min, 0.1 mm/rev and laser power of 1250 W. This decrement in force is due to the workpiece surface temperature Ts in the cutting zone is 880˚C as observed in Table 4. Based on the analysis of the S/N ratio (Fig. 4), the optimal levels of cutting condition for the process parameters are listed in Table 5.

This is due to heat generated by laser power reaches the material yield strength i.e. 650˚C, while in turn results in reduction in forces in all direction. The observed hardness value (48 HRC) of the machined surface showed no significant change before and after LAM. All three components of cutting force are higher in magnitude for higher cutting speed and medium laser power compared to low cutting speed and high laser power. At higher cutting speed and higher laser power, the observed work surface temperature Ts in the shear zone is lower (626˚C) which is below the yield stress reduction temperature 650 ˚C. At medium cutting speed of 75 m/min and laser power of 1250 W, the temperature at the cutting zone is higher which makes the material soft and helps in the removing of material at lower cutting force. Machining of Inconel 718 at medium cutting speed and low laser power is advisable due to the fact that the work surface temperature is between 800˚C- 880˚Cat a feed rate of 0.1 mm/rev. A higher cutting speed

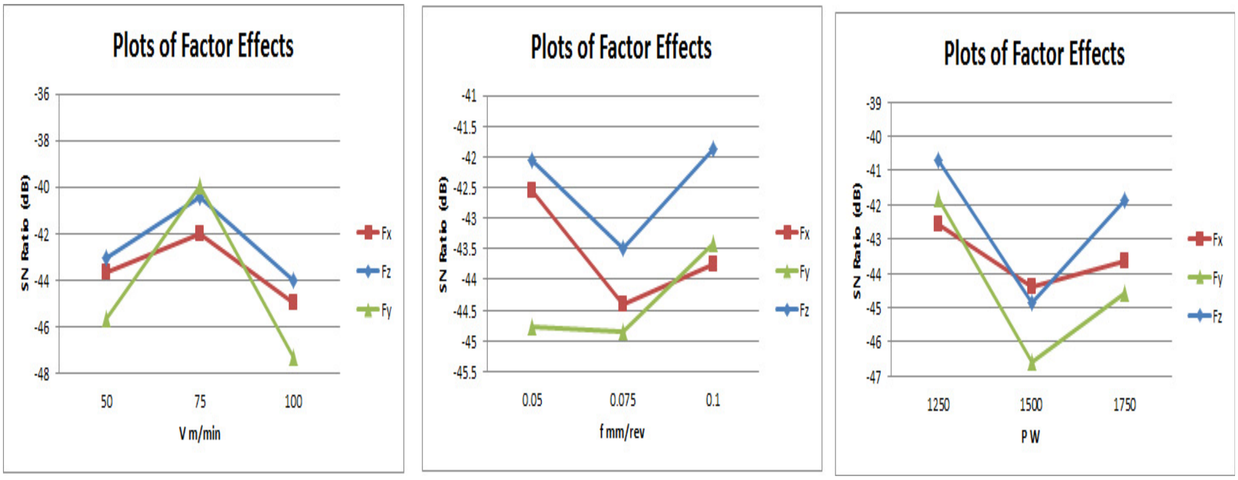


Fig. 4. Plot of Factor effects

is possible with application of laser during turning of Inconel 718 compared to conventional machining without metallurgical damage. Therefore, due to application of laser energy on the work piece the chip gets thinner and decrement in force is observed. The results of analysis of variance for identifying significant factors and its percentage contribution are given in Table 6 and Fig 5. From the ANOVA results for Fx, Fy and Fz, it is evident that the cutting speed is the most significant parameter for affecting force component while the P-value (Probability of significance) is less than 0.05 at 95% confidence level, followed by laser power. The cutting force increases with increase in cutting speed and laser power. However, feed rate is found to be insignificant in the experiments for affecting the responses in the experimental region. The optimum process parameter evolved with respect to minimization of cutting force leads to two different combinations such as s2f1p1 and s2f3p1 respectively.

Table 6 ANOVA Analysis

Source	DF	SS	MS	F ratio	P	%P
Feed Force (Fx)						
Cutting Speed (s)	2	3975.2	1987.6	15.03	0.062	55.04
Feed rate (f)	2	1610.1	805.1	6.09	0.141	22.29
Laser Power (p)	2	1371.5	685.8	5.18	0.162	18.9
Error	2	264.5				3.66
Total	8	7221.4				
Notes: S = 11.5 R-Sq = 96.34% R-Sq(adj) = 85.35%						
Thrust Force (Fy_t)						
Cutting Speed (s)	2	25743.2	12871.6	64.87	0.015	70.45
Feed rate (f)	2	104.1	52.0	0.26	0.792	0.292

Laser power (p)	2	9397.2	4698.6	23.68	0.041	26.36
Error	2	396.8				1.11
Total	8	35641.4				
Notes: S = 14.086 R-Sq = 98.99% R-Sq(adj) = 95.55%						
Cutting Force (F_z)						
Cutting Speed (s)	2	4843.5	2421.7	5.50	0.154	32.92
Feed rate (f)	2	1114.2	557.1	1.27	0.441	7.57
Laser Power (p)	2	7877.9	3928.9	8.95	0.10	53.53
Error	2	879.9				5.97
Total	8	14715.4				
Notes: S = 20.9751 R-Sq = 94.02% R-Sq(adj) = 86.08%						

From the result of the analysis of variance shown in Table 6, the variations caused by each control factor on the cutting parameters as well as the effect of the control factors on the quality characteristic variation can be observed. The main control factors that can effectively reduce the variations and contribute to the quality characteristics are identified in descending order for Fx as feed rate (22.9%), laser power (18.9%) and cutting speed (55.04%), for Fy as feed rate (0.3%), laser power (26.36%) and cutting speed (70.45%), and for Fz feed rate (7.57%), laser power (53.53%) and cutting speed (32.92%).

3.2. Comparison of benefits of LAM and Conventional machining

Fig. 6 shows the percentage reduction of cutting force components (Fx, Fy and Fz) during LAM of Inconel 718 when compared to conventional machining (without laser) for the experimental runs given in Table 4. It is to be noted that for all the experiments there is a reduction of cutting forces during LAM. It could be attributed to the fact that laser source locally soften the work material ahead of the cutting edge before machining. The thermal softening of material in cutting zone helps in reduction of cutting forces. Further it is also observed during LAM that thinner chips are produced which subsequently reduces the cutting forces [29]. For the experiment, Sl. No. 4 it was observed that a reduction of 160.4 N (61%) in the feed direction, 132.3 N (60%) in the thrust direction, and 118.8 N (62%) in the main cutting direction on the cutting tool.

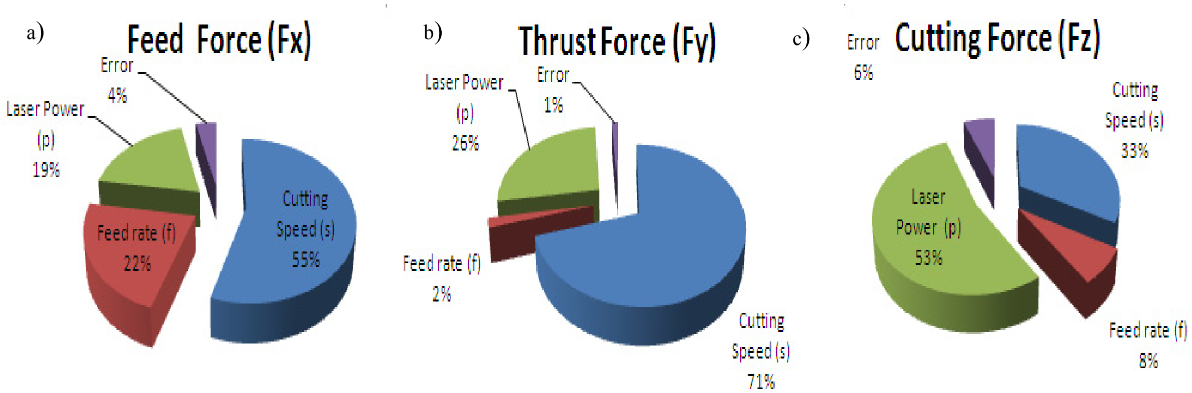


Fig. 5. Percentage contribution on cutting force a) Feed Force (Fx) b) Thrust Force (Fy) c) Cutting Force (Fz)

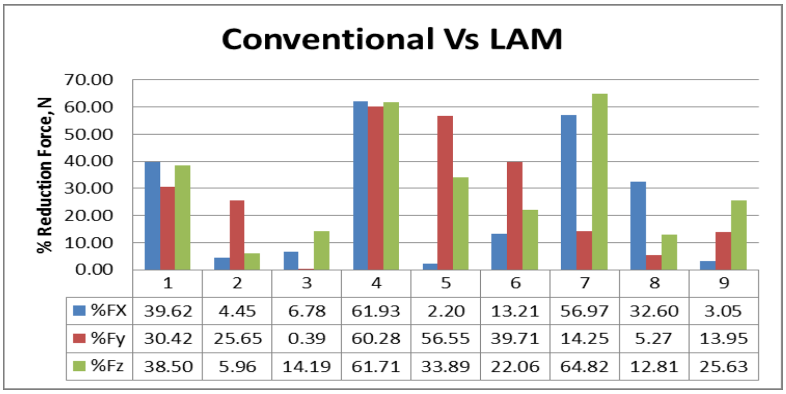


Fig.6a) Force reduction (%) obtained by Conventional Vs LAM of Inconel 718 using varying cutting speeds (s), and feeds (f), for a fixed depth of cut ap=0.5 mm and laser power(p)=1250W

4. Conclusion

This paper discussed about L_9 orthogonal array, S/N ratio and ANOVA were adopted for finding the optimal process parameter for the performance measures of feed force (Fx), thrust force (Fy) and cutting force (Fz).The following conclusions were drawn from the present research:

1. The responses are the uncut temperature, hardness and cutting force. The selected laser cutting parameters include cutting speed, feed rate and laser power.
2. There is a significant decrease in the cutting force. This decrease is more important when the surface temperature is high. The surface temperature depends strongly on the cutting parameters. It increases if the cutting speed, the laser power and the feed rate decrease.
3. Based on the S/N table, main effect plot and ANOVA analysis, the optimal cutting parameter for Fx, Fy and Fz were s2f1p1 and s2f3p1.
4. Cutting speed and laser power was found to be the most significant parameter for Fx, Fy and Fz which accounts the maximum percent contribution of 55% and 19% for Fx, 71% and 26% for Fy and 33% and 53% for Fz. Only for Fx, feed rate account the percent contribution of 22%.
5. At laser power 1250 W with cutting speed 70 m/min and 0.05 mm/min, the benefit of LAM was shown by 61%, 60% and 62% decrease in Feed force (Fx), thrust force (Fy) and cutting force (Fz) as compared to those of the conventional machining.
6. Additionally, it is also recommended to employ a work surface temperature (Ts) in the range of 750˚C–880˚C during LAM of this Inconel 718 alloy to have maximum force reduction. The results also reveals that measured hardness value (48 HRC) of the machined surface showed no significant change before and after LAM.
7. The results of this study would have wide application in laser assisted turning for the machining of difficult-to-cut materials.

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References

[1]E.O. Ezugwu, Key improvements in the machining of difficult-to-cut, International Journal of Machine Tools & Manufacture45 (2005) 1353–1367.

[2] A. Jawaid, S. Koksal, S. Sharif, Cutting performance and wear characteristicsof PVD coated and uncoated carbide tools in face milling Inconel 718aerospace alloy, Journal of Material Processing Technology 116 (2001) 2–9.

[3]D.G. Thakur, B. Ramamoorthy, L. Vijayaraghavan, Study on themachinability characteristics of superalloy Inconel 718 during highspeed turning, Materials and Design 30 (2009) 1718–1725.

[4] MuammerNalbant, Abdullah Altın, HasanGokkaya,The effect of coating material and geometry of cutting tool andcutting speed on machinability properties of Inconel 718 super alloys, Materials and Design 28 (2007) 1719–1724

[5] A. Devillez, F. Schneider, S. Dominiak, D. Dudzinski, D. Larrouquere, Cutting forces and wear in dry machining ofInconel 718 with coated carbide tools,Wear 262 (2007) 931–942.

[6] V. Bushlyaa, J. Zhoua, J.E. Stahla,Effect of Cutting Conditions on Machinability of SuperalloyInconel 718 During High Speed Turning with Coated and UncoatedPCBN Tools,45th CIRP Conference on Manufacturing Systems 2012, Procedia CIRP 3 (2012) 370 – 375.

[7] H.Z. Li, H. Zeng, X.Q. Chen, An experimental study of tool wearand cutting force variation in the end milling of Inconel 718 with coated carbide inserts, Journal of Material Processing Technology 180 (2006) 296–304

[8] Muammer Nalbant, Abdullah Altın, Hasan Gokkaya,The effect of cutting speed and cutting tool geometry onmachinability properties of nickel-base Inconel 718 super alloys, Materials and Design 28 (2007) 1334–1338

[9]J.Costes, Y. Guillet, G.Poulachon, M. Dessoly M, Tool-life andwear mechanisms of cbn tools in machining of Inconel 718 ,International Journal of Machine Tools & manufacture 47(7–8)(2007) 1081–1087

[10] Abhay Bhatt, HelmiAttia, R. Vargas, V.Thomson,Wear mechanisms of WC coated and uncoated tools in finish turning of Inconel 718, Tribology International43(2010)1113–1121

[11]A. M. Ravi, S. M. Murigendrappa and P. G. Mukunda,Experimental investigation on thermally enhanced machiningof high-chrome white cast iron and to study its machinabilitycharacteristics using Taguchi method and artificialneuralnetwork,InternationalJournal of Machine Tools &manufactureDOI 10.1007/s00170-014-5752-4

[12] G. Germain, P. Dal Santo, J.L. Lebrun, Comprehension of chip formation in laserassisted machining, International Journal of Machine Tools and Manufacture51 (2011) 230–238.

[13] H. Ding, Y.C. Shin., Laser-assisted machining of hardened steel parts withsurface integrity analysis, International Journal of Machine Tools and Manufacture50 (2010) 106–114.

[14] P. Dumitrescu, P. Koshy, J. Stenekes, M.A. Elbestawi, High-power diode laserassisted hard turning of AISI D2 tool steel, International Journal of MachineTools and Manufacture 46 (2006) 2009–2016.

[15] F.E. Pfefferkorn, J.C. Rozzi, F.P. Incropera, Y.C. Shin, Surface temperaturemeasurement in laser-assisted machining processes, Experimental HeatTransfer 10 (1997) 291–313.

[16] G. Germain, F. Morel, J.L. Lebrun, A. Morel, B. Huneau, Effect of laser assistancemachining on residual stress and fatigue strength for a bearing steel (100Cr6) and atitanium alloy (Ti6Al4V), Materials Science Forum 524-525 (2006) 569–574.

[17]S.H Masood, Kelly Armitage, Milan Brandt, An experimental study of laser assisted machining of hard to wear white cast iron, International Journal of Machine Tools & manufacture 51 (2011) 450-456.

[18]R.A.Rahman Rashid, S.Sun, G.Wang, M.S. Dargusch,Effect of laser power on machinability of Ti6Cr5Mo5V4Al beta titanium alloy during laser assisted machining, International Journal of machine tools and manufacture 63 (2012) 41-43 .

[19] Virginia Garcia Navas, Iban Arriola, Oscar Bonzalo, Josu Leunda, Mechanisms involved in the improvement of Inconel 718 machinability by laser assisted machining (LAM), International journal of machine tools and manufacture 74(2013) 19-28.

[20] Flaviana Tagliaferri, Giacomo Leopardi, Ulrich Semmler, Michael Kuhl, Biagio Palumbo, Study of influences of laser parameters on laser assisted machining processes, Procedia CIRP 8(2013) 170-175.

[21] H. Attia, S. Tavakoli, R. Vargas, V. Thomson, Laser assisted high speed finish turning of super alloy Inconel 718 under dry conditions, CIRP Annals- Manufacturing Technology 59 (2010) 83-88

[22] Mark Anderson, Rahul Patwa, Yung C. Shin, Laser-assisted machining of Inconel 718 with an economic analysis, International Journal of Machine Tools & Manufacture 46 (2006) 1879–1891

[23] S. Sun, M. Brandt, M.S. Dargusch., Thermally enhanced machining of hard-tomachine materials—a review, International Journal of Machine Tools and Manufacture 50 (2010) 663–680.

[24] R.A. Rahman Rashid, S. Sun, G. Wang, M.S. Dargusch., An investigation of cutting forces and cutting temperatures during laser-assisted machining of theTi–6Cr–5Mo–5V–4Al beta titaniu, alloy, International Journal of Machine Toolsand Manufacture 63 (2012) 58–69.

[25] G. Germain, J.L. Lebrun, T. Braham-Bouchnak, D. Bellett, S. Auger., Laserassisted machining of Inconel 718 with carbide and ceramic inserts, InternationalJournal of Material Forming 1 (1) (2008) 523–526.

[26] B. Shi, H. Attia, R. Vargas, S. Tavakoli, Numerical and experimental investigationof laser-assisted machining of Inconel 718, Journal of Mechanical Scienceand Technology 12 (2008) 498–513.

[27] Dong-Hyeon Kim, Choon-Man Lee, A study of cutting force and pre heating temperature prediction for laser assisted milling of Inconel 718 and AISI 1045 steel International Journal of Heat and Mass Transfer 71 (2014) 264-274.

[28] Ross, T.J. “Taguchi Techniques for quality engineering”, Mc Grawhill, New York, 1996.

[29] Bhatt A., 2006, “Effect of cutting tool coating on machinability of Inconel 718” M. Eng. Thesis, Mcgill University